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Comment [S1]: Elsevier to update and page numbers.**Theoretical and Experimental Analysis of a Vibration
Isolation System Using Hybrid Magnet**
Easu D^{a*}, Siddharthan A^b^aAssociate Professor, Department of Mechanical Engineering, KCG College of Technology, Chennai, India^bAssistant Professor, Department of Mechanical Engineering, College of Engineering Guindy, Anna University, Chennai, India**Abstract**

An active vibration isolation system using hybrid magnet is investigated theoretically and experimentally. A quarter car model with one degree of freedom spring mass system is considered for this analysis. A cylindrical type hybrid magnet, considered as actuator is placed in parallel to the springs to provide external force on the top and bottom plates to suppress vibration. The theoretical time response characteristics of the model have been determined and correlated with experimental analysis. For theoretical analysis, the response of the top plate is analyzed by considering the base plate disturbance as a input signal to vary the actuator force. The force exerted by the hybrid magnet is non linear in nature and the simplified relation for this force was obtained using Bessel's recurrence formula. The modeling of undamped one degree of freedom quarter car model is carried out using MATLAB Simulink tool. The above study is also investigated experimentally by employing a shaker and analyzed using LABVIEW and fast Fourier transform (FFT) analyzer.

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Keywords: Bessel function; Hybrid Magnet; Isolation System; Matlab, Labview;**1. Introduction**

Applications such as automobile, aircraft and communication need high quality isolation system for specific purposes. In general, there are two kinds of disturbances to be avoided by the isolation systems. One is disturbances from ground to the machine and the other is disturbances produced by machines transmitting to the ground.

*corresponding author,
E-mail address: [easu@kcgcollege.com](mailto: easu@kcgcollege.com)

Isolators should maintain the transmissibility ratio which is the ratio of amplitude of the vibrating body to the amplitude of external source below one. This is possible only when the excitation frequency is larger than the natural frequency of the system [1].

Nomenclature

m	mass of the top plate
k	stiffness of the spring
f_d	force between electromagnet and permanent magnet
α	constant
h	thickness of the permanent magnet
t	thickness of the flange
R_1	Inner radius of electromagnet
R_2	outer radius of electromagnet
R_3	inner radius of permanent magnet
μ_r	permeability of coil
i	coil current
l	core height
g	gap between electromagnet and permanent magnet

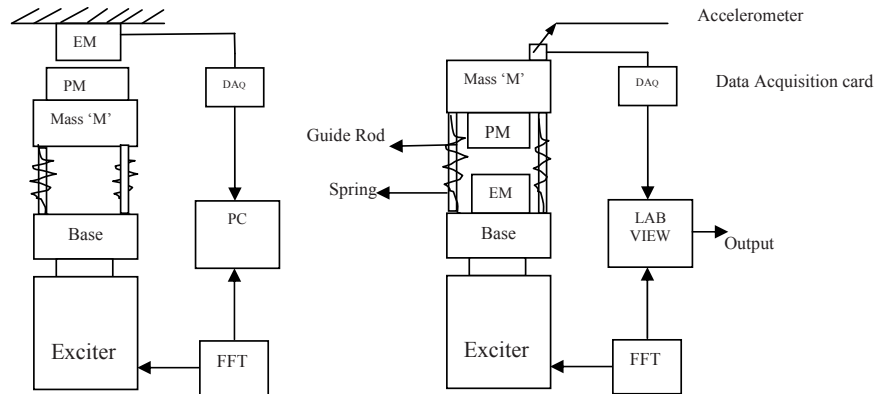
1.1. Isolation system

Conventional isolation system also known as passive system uses springs and dampers as isolators. The performance of the passive systems are limited because, various trades off are necessary when excitations with a wide frequency range are involved. Active isolation system uses active elements such as actuators, sensors and controllers to resolve drawbacks in the conventional systems. In semi active isolation system, Magneto Rheological Fluids (MR Fluid) and Electro Rheological Fluids (ER Fluid) are used as external source to reduce the vibration. In active suspension system, external force is applied by means of actuators to suppress the vibration. Hydraulic, Pneumatic and Magnets are used as actuators in active isolation system. Vibration isolation systems with different combination of conventional elements, semi and active elements have been investigated by many researchers. A survey has been taken by on the types of suspension such as passive, semi active, and active with different types of actuator forces. All the above combinations have been investigated on different models such as quarter car, half car and full car models [2]. The response to be considered in the vibration analysis is different for different applications. For example vertical displacement is considered as response for studying vibration of cutting tools whereas cutting force as input vertical acceleration is considered as response to be reduced in vibration analysis of automobile suspension system [3].

The magnetic levitation principle has wide range of applications, such as the suspension system for super high speed bullet trains, dust free carriers in clean rooms, magnetic bearings and so on. Such isolation system has no mechanical contact problems and has many advantages of non contact suspension and propulsion systems through direct application of electromagnetic forces. Masao and Seiki [4] analyze, theoretically and experimentally, the effectiveness of actively controlled air suspension applied to repulsive type Maglev vehicle systems. Many investigations have been made on magnetic suspension isolation by Mizuno *et al.*, [5]. In their research negative stiffness of hybrid magnet, linear actuator, zero power control was discussed. Kim *et al.*, [6] discussed the theoretical approach of cylindrical magnet using perturbation technique and also the position and current stiffness of the hybrid magnet were found theoretically using transfer function technique. Mache and Joshi [7] found the values of position stiffness and current stiffness of the force between electromagnet and permanent magnet experimentally and analyzed the frequency response of the two degree of freedom system. Both Kim *et al.*[6], and Mache and Joshi[7] used experimental values to find the position and current stiffness and also the response of the

Table 1 One degree of freedom quarter car model parameters

Parameters	Units	Values
Top plate mass	kg	10
Spring Stiffness	N/m	387
Number of turns	No unit	2800
Electromagnet coil(Standard Wire Gauge-(swg))	swg	19
Core height of the electromagnet	mm	100
Outer diameter of the electromagnet	mm	120
Inner diameter of electromagnet	mm	60
Thickness of flange	mm	10
Relative Permeability of the coil	no unit	0.9999
Inner diameter of permanent magnet	mm	80
Thickness of the permanent magnet	mm	20

Fig.2 One degree of freedom isolation system (a) Kim *et al.* experimental setup [6] and (b) proposed experimental setup

'I' is coil current, 'x' is vertical displacement of top plate. ' α ' and 'n' are constants which depend on the magnet shape, permeability of the electromagnet coil, number of turns and coil current.

$$\alpha = \frac{3}{2} \frac{\mu_2 M_o N R_1}{n l (R_2 - R_1) J_1(n R_1)} e^{-nt} (1 - e^{-h}) \int_{R_3}^{R_2} [-J_0(nr) + (nr) J_1(nr)] dr \quad (2)$$

To find the solution f_d , the integral part of α is calculated using Bessel's integral formula as follows,

$$\begin{aligned} & \int_{R_3}^{R_2} [-J_0(nr) + (nr) J_1(nr)] dr \\ &= \frac{1}{n} \int_{R_3}^{R_2} [-J_0(nr) + nr J_1(nr)] d(nr) \\ &= -r J_0(nr) \Big|_{R_3}^{R_2} \\ J_0(nr) &= 1 - \frac{(nr)^2}{2^2} + \frac{(nr)^4}{2^2 \cdot 4^2} - \dots \end{aligned} \quad (3)$$

Here $n = \frac{2.45}{R_1}$ as reported by Kim *et al.* [6]. In the equation number (3) only the first two terms are considered.

Higher powers of the term nr do not affect the system response so they are neglected. The force between electromagnet and permanent magnet is then;

$$f_d = \frac{3}{2} \frac{\mu_2 M_o N R_1}{nl(R_2 - R_1) \left\{ \frac{nR_1}{2} - \frac{(nR_1)^3}{2^2 \cdot 4} \right\}} e^{-nt} (1 - e^{-h}) \left\{ -R_2 \left\{ 1 - \frac{(nR_2)^2}{2^2} \right\} + R_3 \left\{ 1 - \frac{(nR_3)^2}{2^2} \right\} \right\} \times I e^{-nx} \quad (4)$$

In the above expression all the parameters are constant except the current (I) and the gap between electromagnet and permanent magnet(x). If the value of current is kept constant then the Laplace transform of f_d is

$$L[f(\alpha I e^{-nx})] = \frac{\alpha I}{s + n} \quad (5)$$

The MATLAB Simulink block diagram of Eq. (1) is shown in Fig 3. Here the input is provided as a sinusoidal signal with an amplitude and frequency of 10 mm and 10 Hz respectively.

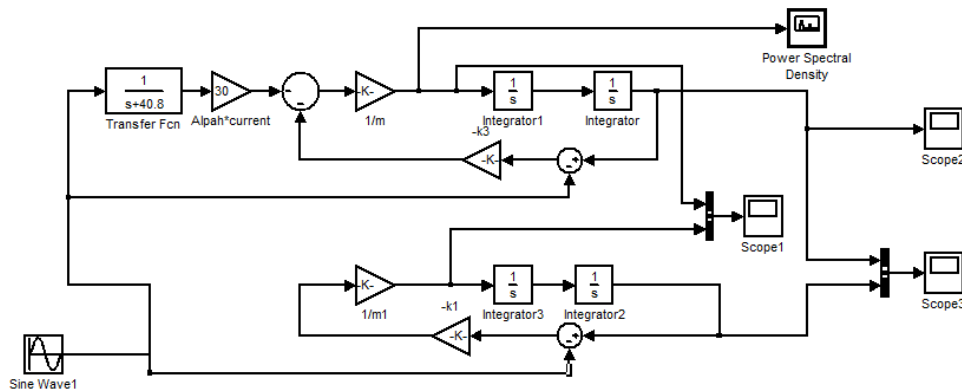


Fig.3 Block diagram of MATLAB Simulink

3.Validation of the force relation

A relation for force between electromagnet and permanent magnet was arrived by linearization technique by Kim *et al.*, [6]. But in actual practice the force between the magnets are non linear. In this work instead of linearization technique, the solution of Maxwell equation for the cylindrical type magnet is obtained using Bessel's recurrence formula. A simplified relationship for nonlinear force between electromagnet and permanent magnet was obtained using Bessel's recurrence formula and the Laplace transform of the force was used in the theoretical analysis. The relation was validated using the setup used in Kim *et al.*, [6] (Fig.1) theoretically and same is validated using experimental results. The one degree of freedom system model was analyzed theoretically in MATLAB including the actuator force. Coil current is kept as constant and frequency is varied.

The fabricated setup of a single degree of freedom spring mass system placed on an exciter (shaker) is shown in Fig.4. Three guide rods are used to guide the vertical motion of the upper plate and also to avoid the lateral motion of the plates. A cylindrical type electromagnet was fixed above the base plate and a permanent magnet was fixed on bottom side of top plate. Both electromagnet and permanent magnet were allowed to move vertically on the guide rods. An AC-DC rectifier with an auto transformer is used to vary the coil current. Sinusoidal road input of frequency 1 to 10 Hz is given to the base. Accelerometer is placed on the top plate and base plate and the signals were received through DAQ card and analyzed in LabView 6.1 Version. The response of the top plate and bottom plate are obtained for 10kg load and are plotted. Both time and frequency domain output are compared with the results.



Fig.4 Experimental Setup

4. Results and Discussion

Table 2 and Fig.5 shows the validation of the new relation and it is better than that the relation proposed by Kim *et al.*, [6] which is almost straight line. Theoretical and experimental results of the present work indicate non linearity of the force between electromagnet and permanent magnet.

Table 2. Displacement of top plate by Kim *et al.* setup and proposed setup with different excitation frequencies

Frequency (Hz)	Proposed experimental set up				Kim <i>et al.</i> experimental setup	
	DBT (mm) (Experimental)	DTP without current (mm) (Experimental)	DTP (mm) (Theoretical)	DTP (mm) (Experimental)	DTP (mm) (Theoretical)	DTP (mm) (Experimental)
2	0.46	0.36	0.15	0.26	0.2	0.38
4	0.58	1.47	0.5	0.517	0.25	0.30
6	0.7	0.5	0.35	0.266	0.3	0.25
8	0.8	0.5	0.2	0.197	0.3	0.18
10	0.8	0.5	0.1	0.059	0.25	0.09

DBP- Displacement of Base plate; DTP- Displacement of top plate with electromagnet

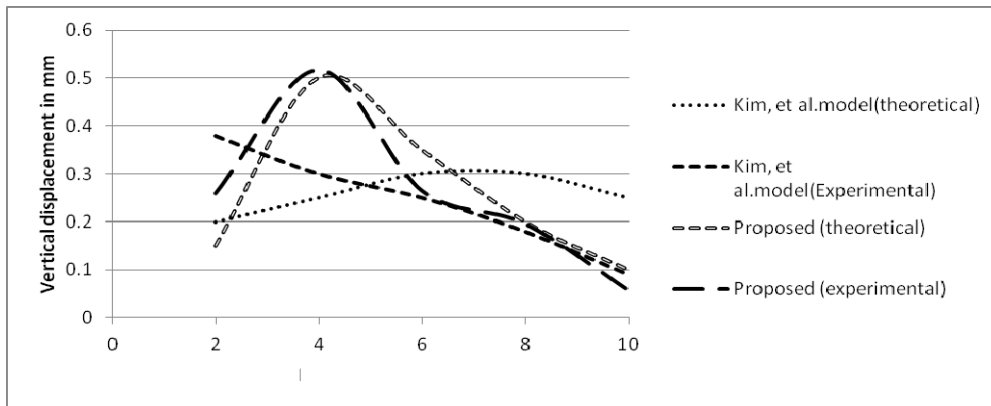


Fig.5. Comparison of experimental and theoretical displacement values of top plate for different base plate excitation

Figure 6 and 7 show the vertical displacement of top plate for a coil current of 1 amps at a frequency of 2Hz. Figure 8 and 9 shows the vertical displacement of top plate for a coil current of 1amps at a frequency of 4Hz. In both frequencies the proposed setup reduces the displacement of top plates. Figure 10 and 11 shows the theoretical response of the top plate. The displacement of top plate in proposed setup is less than Kim *et al.* experimental setup values. Both theoretical and experimental results of proposed system illustrate the response of the non linearity force on the top plate. This can be controlled if proper feedback controller is used.

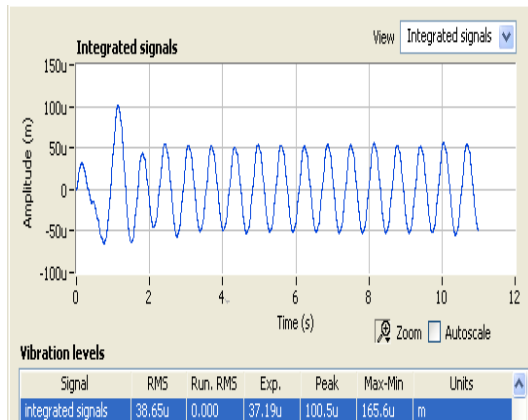


Fig. 6 Top plate response of Kim *et al.* system -2Hz(experimental)

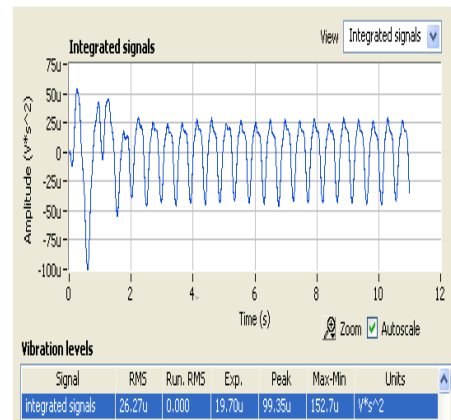


Fig.7 Top plate response of Proposed system-2Hz(experimental)

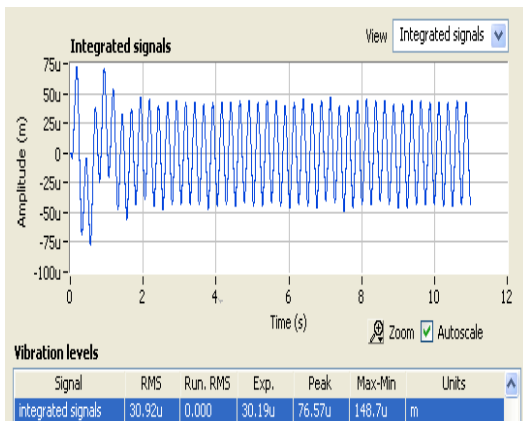


Fig.8 Top plate response of Kim *et al.* system -4Hz(experimental)

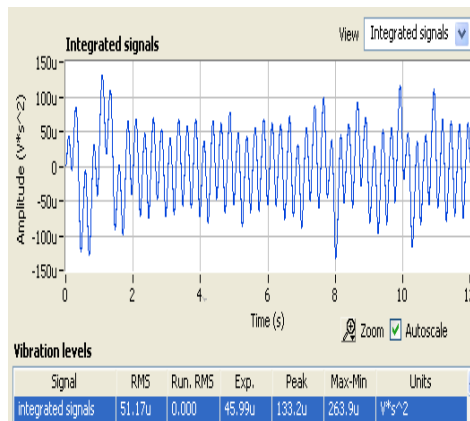


Fig.9 Top plate response of Proposed system 4 Hz(experimental)

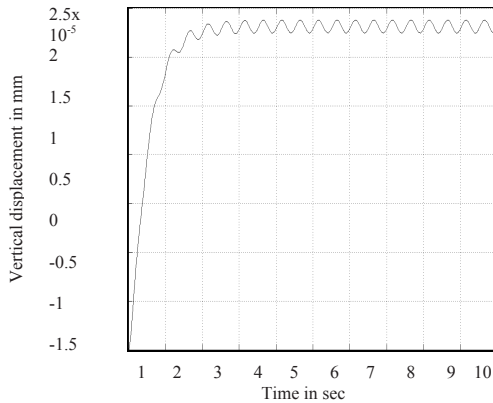
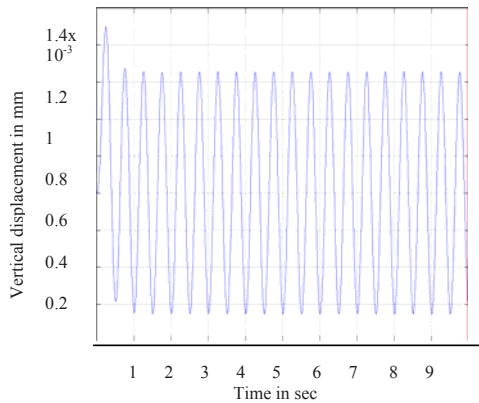
Fig. 10 Theoretical response of top plate at 2Hz- Kim *et al.* system

Fig. 11 Theoretical response of top plate at 2Hz - proposed system

5. Conclusion

In this paper, theoretical and experimental studies on the response of an active isolation system with one degree of freedom quarter car model were analyzed with and without hybrid magnet. A relationship for the nonlinear force between electromagnet and permanent magnet was arrived and validated. The response of the system using the above relationship was then obtained theoretically and also verified experimentally. It is observed from the various results that the use of hybrid magnet reduces the amplitude of vibration over a wide range of frequency. The nonlinear force between electromagnet and permanent magnet reduces the system response considerably.

References

- [1] J.P.Denhartog, "Mechanical Vibrations" Dover Publications Inc., New York, 1985.
- [2] D.Hrovat, "Survey of Advanced Suspension Developments and Related Optimal Control Applications," *Automatica*, 1997, Vol.33, No.10, pp 1781-1817.
- [3] Ashok Kumar Mallik, "Principles of Vibration Control", Affiliated East - West Press (P) Ltd., New Delhi, 1990.
- [4] Masao Nagai and Seiki Tanaka, "Study on the Dynamic Stability of Repulsive Magnetic Levitation Systems," *JSME International Journal*, 1992, Series III, Vol.33, No.1, pp.102-108.
- [5] Takeshi Mizuno, Masaya Takasaki, Daisuke Kishita, Keiichi Hiraoka, "Vibration Isolation System Combining Zero-Power Magnetic Suspension with Springs", *Control Engineering Practice*, 2007, 15, pp.187-196.
- [6] Y-B Kim, W-G Hwang, C-D Kee and H-B Yi, "Active Vibration Control of a Suspension System Using an Electromagnetic Damper," *Proc.Instrn.Mech.Engrs.*, 2001, Vol 215, Part.D., pp.865-873.
- [7] A.R.Mache, S.G.Joshi, "Theoretical and Experimental Dynamic Response Analysis of a Road Vehicle Suspension System Using an Electromagnetic Damper," *SAE International*. (SP-2146) 2007-01-4271.